Tidal Channel Dynamics and Muddy Substrates: A Comparison between a Wave Dominated and a Tidal Dominated System

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LONG-TERM GOALS

- To link the geotechnical properties of sediment substrates to the spatial and hydrodynamic characteristics of tidal channels
- To develop new morphological indicators of tidal flat morphodynamics that can be easily derived from remote sensing images. To link these indicators to mechanical properties of tidal flat substrates

OBJECTIVES

- To quantify the relationships between resuspension of fine material in the shelf by wind waves, tidal channels hydrodynamics, and sediment supply to coastal marshes.
- To determine the relationship between wind waves and sediment dynamics in mudflats
- To develop predictive, high-resolution models for the hydrodynamics and sediment dynamics of tidal channels and runnels in mudflats

APPROACH: FIELD COMPONENT

We have determined how tidal fluxes and waves affect the distribution of channels in muddy environments and, vice versa, how tidal channels modify tidal circulation and wave distribution. Moreover our project sheds light on the relationship between the mechanical properties of the mud substrate and intertidal morphology. To accomplish this task we have compared two mud dominated environments. Little Constance Bayou, in Louisiana, and Willapa Bay, in Washington State. In Little Constance Bayou waves propagating from offshore resuspend sediments near the shoreline, this sediment is then funneled in tidal channels reaching the marsh interior. In Willapa Bay the large tidal excursion is the driving mechanism for sediment transport.

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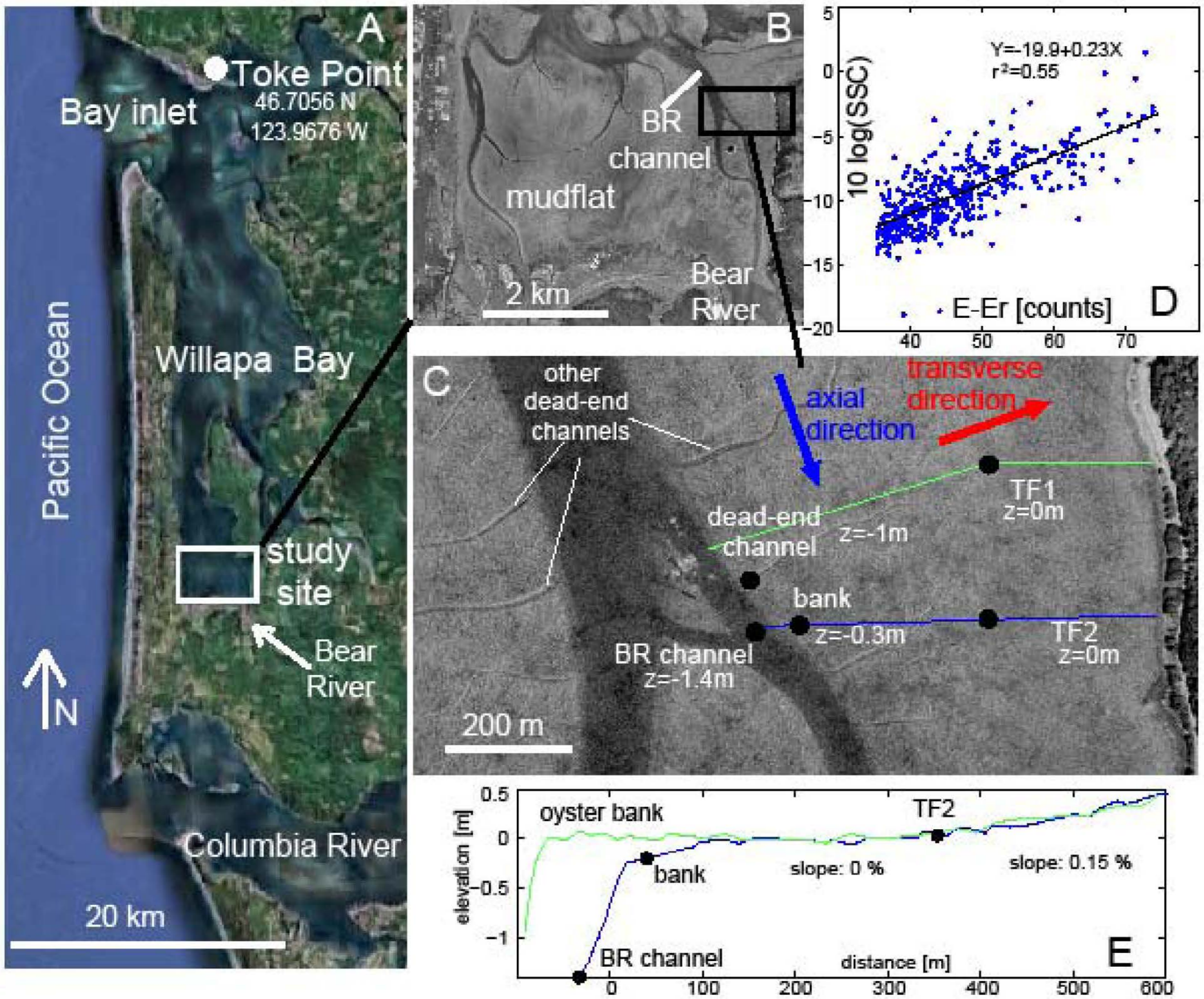

Figure 1. A) Willapa Bay study site, Washington State, USA. B) Detail of the inner mudflat of Willapa Bay. C) Instrument deployment with the locations of the five ADCPs. D) Calibration of the ADCP backscatter with the suspended sediment concentration. E) Topographic transect derived from a local survey. The location of the transect is shown in Fig 1C.

We have spent fiscal year 2010-2011 and 2011-2012 analyzing the large volume of data collected in Willapa Bay in 2010. Five Acoustic Doppler Current Profiler (ADCP) were deployed for 46 days (from 2/21 to 4/9 2010) for a total of 90 tidal cycles in Willapa Bay, Washington State, USA. Two ADCPs were placed on the tidal flat (TF1, TF2), one at the mouth of a dead-end channel, one inside the BR channel, and one on the tidal flat next to the BR channel (channel bank) (Fig 1C). The ADCPs were deployed directly on the bed surface in the upward looking configuration. Near the bank site the BR channel bifurcates in two branches, which reconnect after 1 km. The east branch is about 60 m wide and 2 m deep with respect to the tidal flat, the west branch is about 80 m wide and 3 m deep. The ADCP in the BR channel was deployed in the east branch (see Fig 1C). Finally, an Optical Backscatter Sensor (OBS) was deployed with the ADCP in the dead-end channel at 20 cm from the channel bottom.

A topographic survey reveals that the mudflat is approximately flat along the N-S direction, at the spatial scale of the tidal flat width (500 m). A bottom slope is present in the W-E direction, but only within the last 250 m close to the landward boundary, varying gradually from 0.1% to 1% (Fig 1E). The mudflat is placed 0.7 m below mean sea level (MSL), and its elevation is set herein equal to zero in a local coordinate system. The two instrument sites on the tidal flat are placed at the same elevation; the bottom of the dead-end channel is 1m below the tidal flat, the bank site (low tidal flat) is 0.3m below the tidal flat, and the site in the BR channel is 1.4 m below the tidal flat elevation.

Velocity profiles were measured with the ADCPs at 2 Hz every 30 minutes, averaging over 60 s, with a vertical cell size of 10 cm and a blanking distance of 10 cm. Water depth was calculated using the pressure measured by the ADCPs' piezometers. The pressure was corrected with the atmospheric pressure measured at the NOAA station at Toke Point (station 9440910). Water level was obtained by adding the bed elevation (measured during the survey) to the water depth.

At every location, a wave burst of 512 points was hourly sampled at 2 Hz. The surface wave spectrum was reconstructed from each wave burst using the standard linear wave theory.

Suspended sediment concentration (SSC) was estimated using the backscatter signal of the ADCP and the turbidity value measured by the OBS when present.

The OBS turbidity signal was calibrated against SSC measured in a laboratory tank, using sediments collected on the tidal flat. The OBS was present only at the dead-end channel site.

INTERPLAY BETWEEN WAVES AND TIDAL CHANNEL HYDRODYNAMICS ALONG THE LOUISIANA COAST

To determine the relationship between waves, sediment resuspension, and sediment fluxes to marshes along a muddy shoreline we deployed 5 instruments in Little Constance Bayou, Louisiana from 10/14/11 to 11/26/11.

The instruments were placed in a nested configuration, following the hierarchical structure of the network. The goal of this deployment was to follow the tidal and sediment signal along the channel network, from wave resuspension events in the ocean, to increasingly smaller channels until the water debouches in low laying areas inside the marsh. High levees disconnect the largest channels from the marsh interior, so that tidal fluxes are able to reach internal ponds only through the channel network (Fig. 2). We believe that during this process part of the sediment in suspension is deposited along the way, so that very little sediment reaches the ponds.

A RBR wave gauge recorded wave climate during the deployment at 4Hz every hour. ADCP3 with two OBSs was deployed at the river mouth (width 22m), recording tidal velocities and sediment concentration every 30min. ADCP1 was deployed in a first order tributary (width 10m), ADCP4 in a second order tributary (width 4m) , and ADCP2 in the smallest (width 2m) with the same configuration of ADCP3 .

In collaboration with Alex Kolker at LUMCON we also collected cores and surficial samples along four transects (Fig. 2b). Measurements of Radon isotopes in the sediment samples before and after the deployment will allow us to determine sediment deposition rates at different locations during the study. All data are currently processed at Boston University and LUMCON.

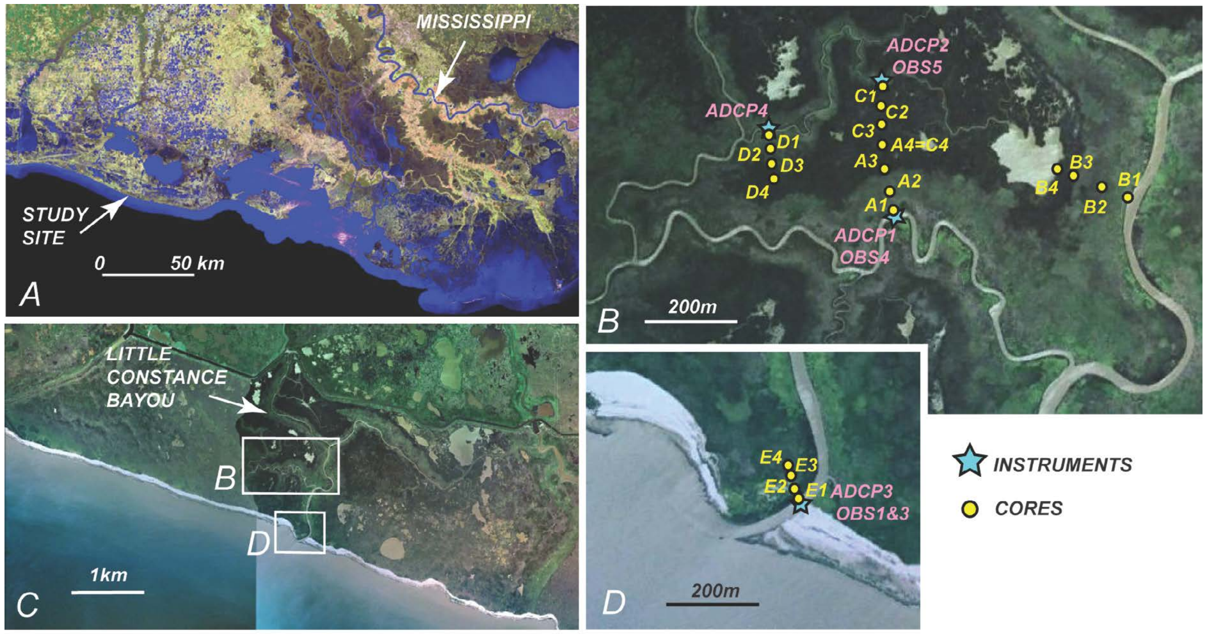

Figure 2 Instrument deployment in little Constance Bayou, Louisiana. A) and C) location of the study site along the chenier plain coastline, B) and D) detail of the field sites. The locations of the ADCPs and four transects are indicated.

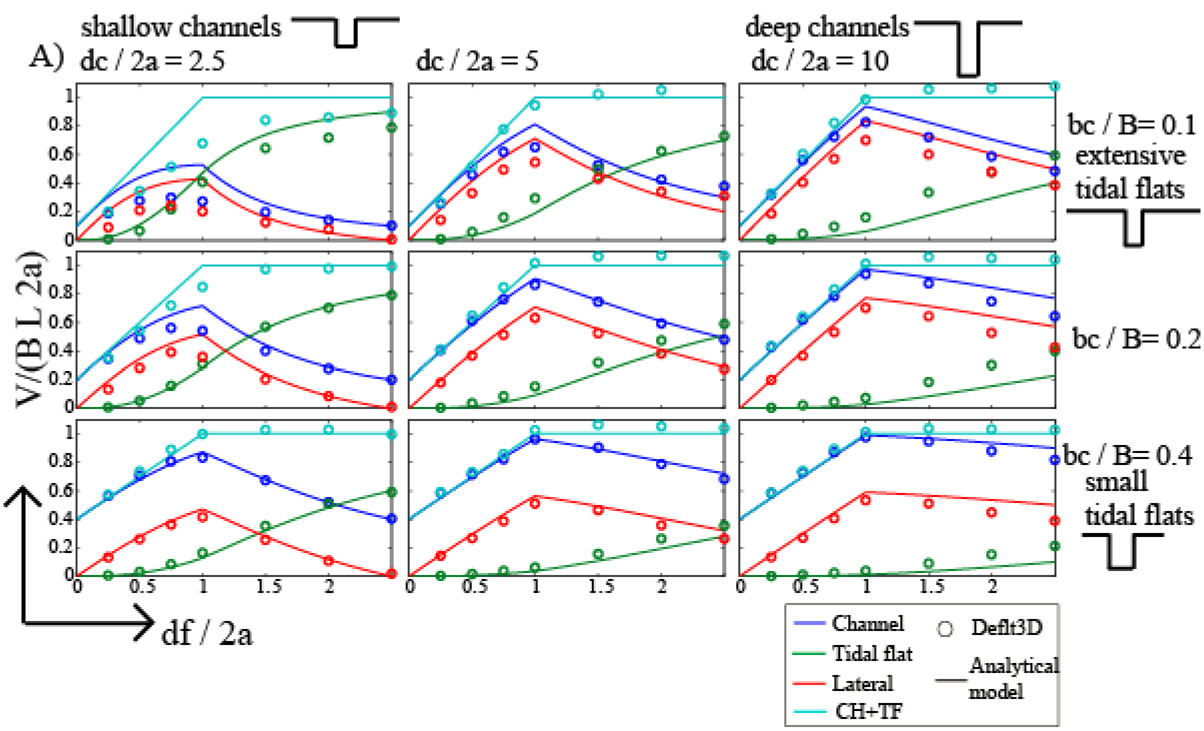

Figure 3. Normalized exchanged volumes (channel, tidal flat, and lateral) as a function of nondimensional channel width, channel depth, and tidal flat depth. Continues lines are the analytical model, dots are Delft3D simulations (after Mariotti and Fagherazzi 2012c)

APPROACH: MODELING COMPONENT

A DYNAMICAL MODEL FOR THE COUPLED EVOLUTION OF CHANNELS AND TIDAL FLATS

We have developed a dynamical model for the morphological evolution of channels and tidal flats. Both channels and tidal flats are schematized as sediment reservoirs, whose depths are the only two dynamical variables of the system. The two reservoirs exchange sediments through the tidal dispersion mechanism. The reference concentrations are determined by currents and waves, which are function of the geometry of the system. The hydrodynamic component of our simplified model is compared to the numerical model Delft3D, showing good agreement (Fig. 3).

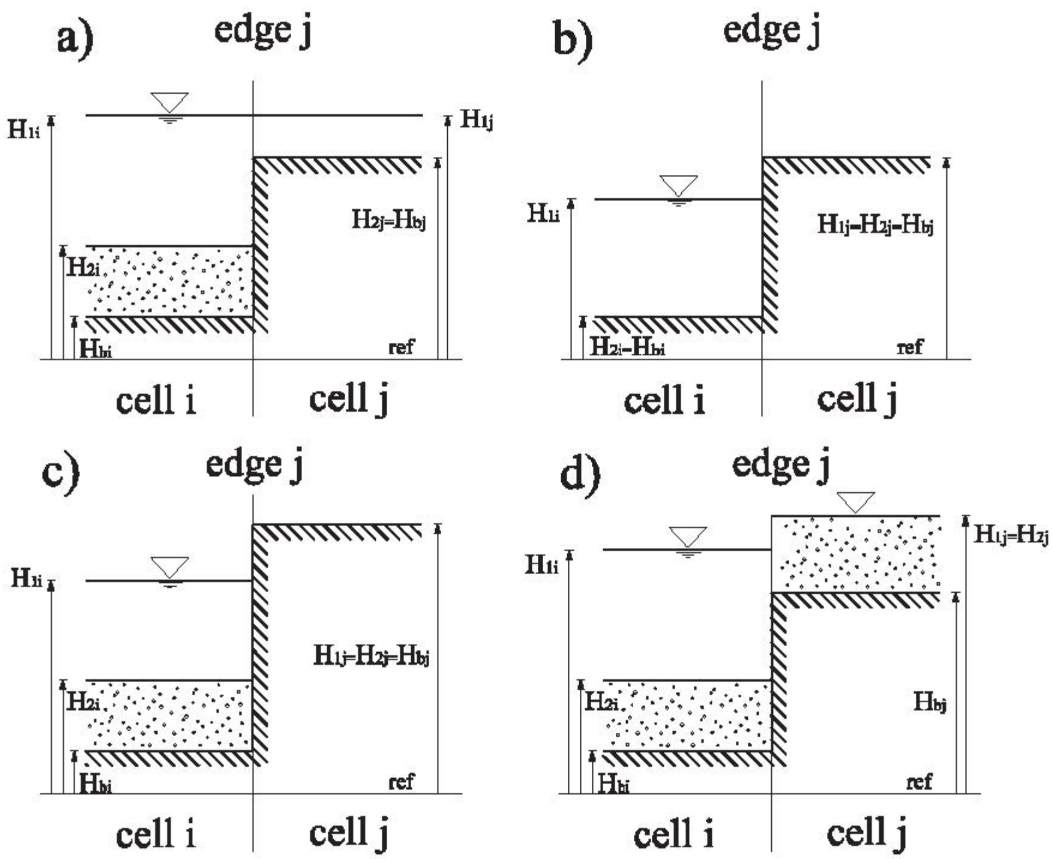

Figure 4. Section normal to a mesh edge of the finite volume model, showing possible wet/dry transitions. (a) The fluid mud layer vanishes over an emerging bed. (b) The water layer vanishes over an emerging bed. (c) Both the water and the fluid mud layers vanish over an emerging bed. (d) The water layer vanishes over an emerging fluid mud layer. This latter case can occur only if the fluid mud behaves as a Bingham fluid (after Canestrelli et al 2012).

A MASS-CONSERVATIVE CENTERED FINITE VOLUME MODEL FOR FLUID MUD PROPAGATION OVER VARYING TOPOGRAPHY AND DRY AREAS

We have also developed a finite volume model to solve the two-dimensional shallow water equations governing the propagation of two superimposed layers, with the upper water layer carrying a dilute sediment suspension, and the underlaying layer being a high concentration non-Newtonian fluid mud mixture. We applied the FORCE-contact method developed by Canestrelli and Toro (2012) to the two-layers system of water and fluid mud. The dynamics of the two superimposed layers is based on the theory of Winterwerp et al. (2002). The FORCE-contact method provides accurate results of high order while respecting the physics of wave propagation across discontinuous boundaries. The method was improved to account for wetting and drying processes of both water and mud layer, as well as for the wet/dry transition between water and mud. Our framework has the following characteristics: (i) the model is stable even under small non-hyperbolicity; (ii) the model is well-balanced, fulfilling the C-property when the liquids are quiescent; (iii) the model conserves mass during flooding and drying on complex geometries; (iv) the model correctly reproduces available analytical solutions for the lock exchange problem and the dam-break with two superimposed liquid layers in the reservoir; (v) the model can also simulate the dynamics of a dam-break with two liquid layers over a dry bed with complex geometry.

MODELING THE INFLUENCE OF FETCH AND DEPTH ON WAVES DEVELOPING IN MUDFLATS

The wave spectral model SWAN was applied to the Willapa Bay mudflats in a simplified 1D bottom geometry, reproducing with good agreement the measured wave characteristics. Depending on wind direction, waves are locally generated on the tidal flat or propagated from adjacent areas, characterized by longer fetches and higher water depths. Using SWAN parametrically, this different behavior is explained in terms of fetch.

RESULTS

THE CHANNEL SPILLOVER MECHANISM IN MUDFLATS Suspended sediment concentration (SSC) shows a recursive pattern between different tidal cycles (Fig.5). We measured a lateral circulation between a large flow-through channel and the adjacent tidal flat in Willapa Bay (Fig. 1). The corresponding fluxes are characterized by higher velocities at the beginning of the tidal flat inundation and at the end of the tidal flat drainage (see also Nowacki and Ogston, 2011). A simplified barotropic model suggests that this lateral circulation is generated by the differential longitudinal velocities between the main channel and the tidal flat. This model allows estimating the lateral circulation by continuity arguments only, without knowing the form of the tidal wave propagation.

The lateral circulation is characterized by a flux of sediment directed from the channel to the tidal flat during flood. This flux likely originates from the elevated SSC in the channel and is transported across the bank without significant change. The advection of sediment from the channel contributes to the formation of the turbid tidal edge measured on the tidal flat (Hsu et al. 2001).

Even though observations suggested the importance of sediment advection from channels (e.g. Ridderinkhof et al., 2000, Warner et al. 2004), this contribution was never emphasized and described in detail, and has not been related to the formation of the turbid tidal edge.

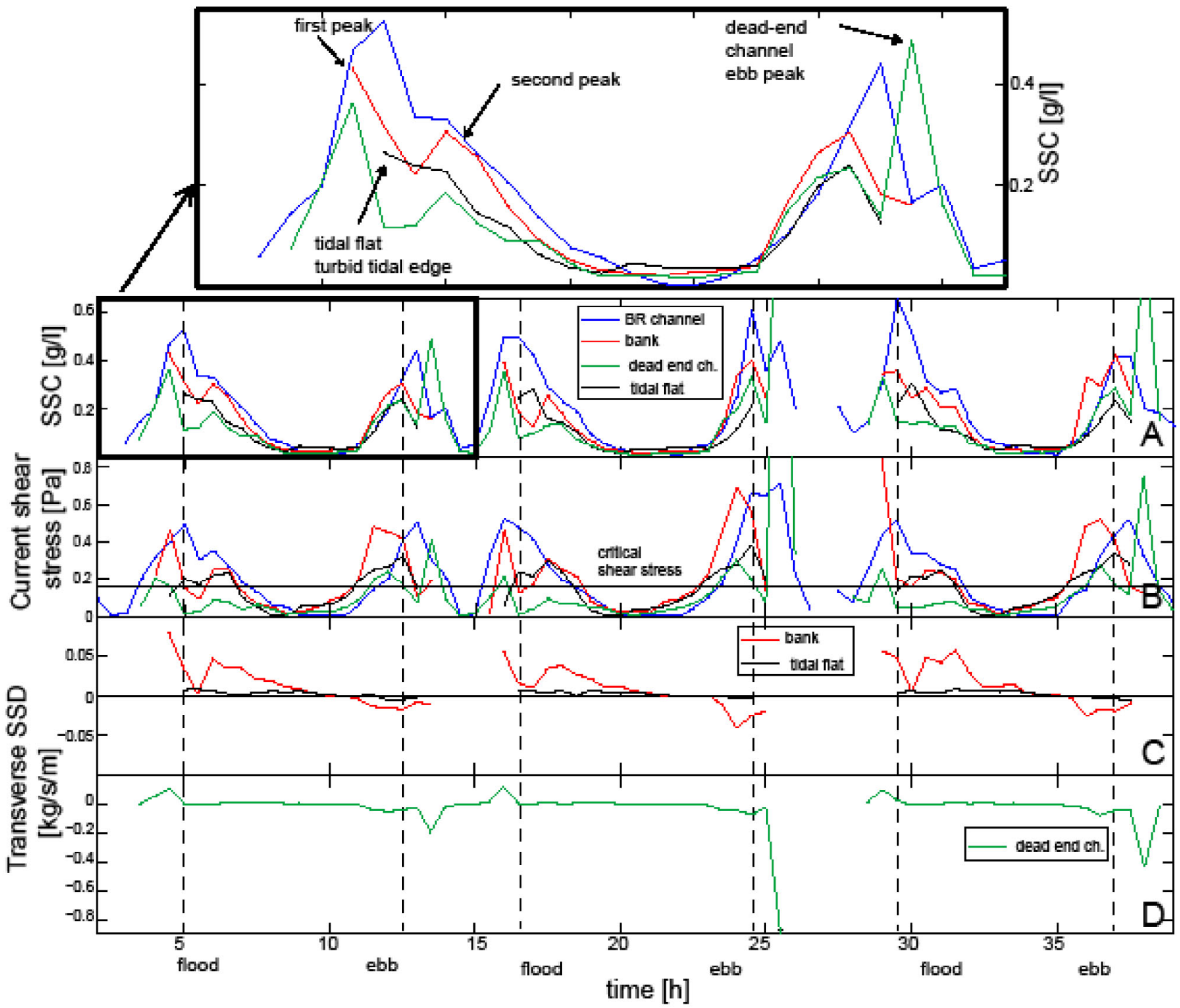

Figure 5. Suspended sediment concentration (SSC) measured from 3/3 to 3/6 2010 at different locations. A) SSC in the channel, bank, dead-end channel and tidal flat. B) Current induced shear stress in the channel, bank, dead-end channel and tidal flat. The horizontal black line defines the critical shear stress, set equal to 0.15 Pa. C) Transverse suspended sediment discharge at the bank and on the tidal flat. D) Transverse suspended sediment discharge in the dead-end channel (after Mariotti and Fagherazzi 2012a).

We propose a simple mechanism, which stems from two conditions: 1) higher SSC in the main channel than on the tidal flat, 2) water diverging from the channel during flood and converging during ebb. According to the channel spillover mechanism, sediments are brought from the main channel to the tidal flat during flood, but not during ebb, generating a net accumulation on the tidal flat.

This mechanism can either act independently or interact with other sedimentary processes present on the tidal flat. Tidal asymmetries in duration, velocity, or stratification are not altering the mechanism, provided that conditions 1) and 2) are present. However, the presence of wind waves increases SSC on the tidal flat more than in the tidal channel, reversing the channel spillover mechanism. Is therefore clear that a complete understanding of the tidal flat sediment dynamics requires the coupling between these processes.

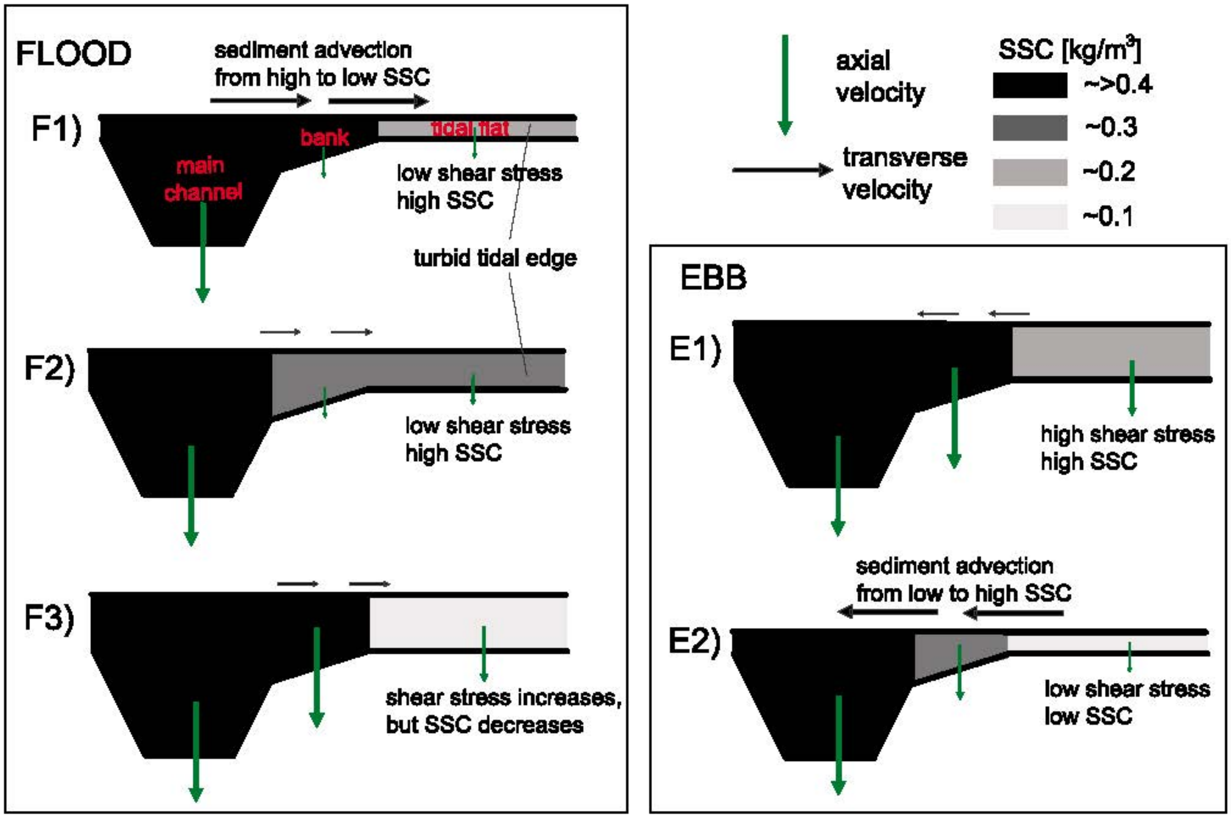

Figure 6. Diagram describing the channel spillover mechanism. Axial velocities and Suspended Sediment Concentration (SSC) are greater in the channel than on the tidal flat during both ebb and flood. Transverse flow is directed from the channel to the tidal flat during the early flood (F1) and from the tidal flat to the channel during the late ebb (E2). During F1, the sediment advection is a positive term for the SSC budget on the tidal flat and contributes to the formation of the turbid tidal edge, while during E2, the sediment advection is a negative term for the SSC budget in the BR channel. During midflood (F3), high longitudinal velocities on the bank can generate a secondary SSC peak. However, because of the small transverse velocity, the resulting sediment discharge does not substantially increase SSC on the tidal flat (after Mariotti and Fagherazzi 2012a).

INFLUENCE OF FETCH AND DEPTH ON WAVES DEVELOPING IN MUDFLATS

The relationship between bed shear stress generated by short waves and water depth shows a dependence on fetch: the decay of bed shear stress with increasing water depth is gradual for long fetch and rapid for short fetch.This difference is explained by the combined effects of water depth, wave height and wave period. Due to the fetch-dependent bed shear stress, different morphological consequences for tidal flats of different size are predicted. In small (<2 km) and sheltered tidal flats, waves cause the largest sediment resuspension when water levels are near mean sea level. In extensive tidal flats(>20 km) or in flats exposed to waves propagating from deep water, waves generate substrate erosion during high tides or large sorm surges.

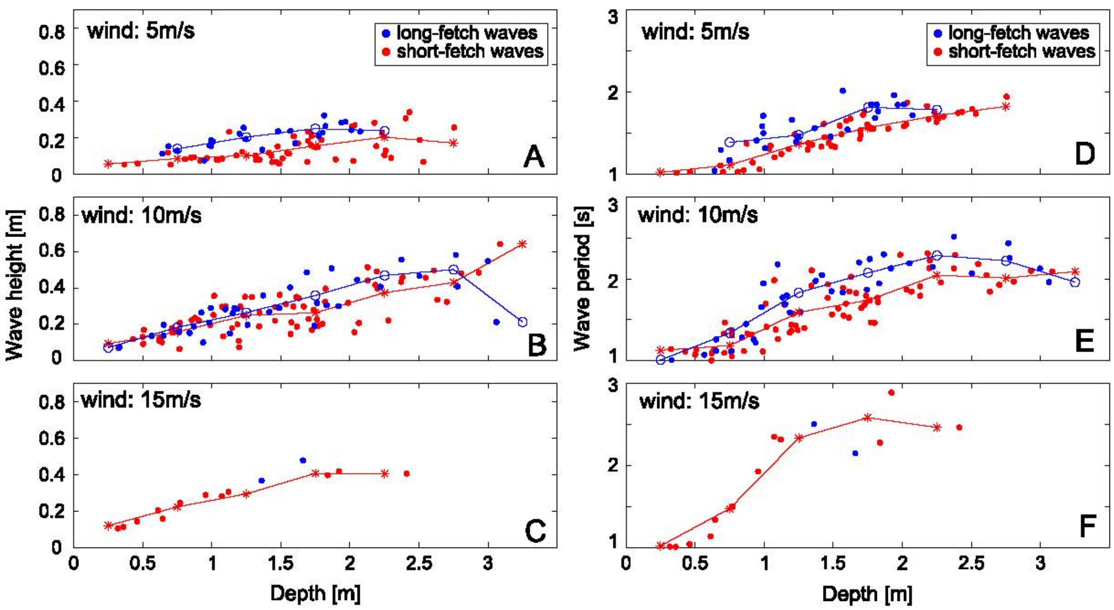

Figure 7. Bed shear stresses measured and predicted on the Willapa Bay mudflat by the SWAN model as a function of water depth, subdivided in 3 classes of wind speed: (A) 2.5 to 7.5m/s; (B) 7.5 to 12.5 m/s; (C) 12.5 to 17.5m/s. (D) Bed shear stress simulated with SWAN for winds of 5 m/s; (E) for winds of 10m/s; and (F) for winds of 15m/s. Red dots represent short-fetch waves and blue dots represent long-fetch waves. The stars and the circles are the average of local wave parameters binned every 0.5m of depth (after Mariotti and Fagherazzi 2012b).

EVIDENCE AND IMPORTANCE OF VERY SHALLOW FLOWS IN MUDFLAT RUNNELS

High resolution data of tidal velocity and sediment concentration measured in a mudflat runnel in Willapa Bay, Washington State, USA, indicate that very shallow flows draining the mudflat platform are concentrated in runnels. These flows, with water depths of few tens of centimeters, are characterized by velocities close to the flood and ebb maxima associated to the regional flow when the mudflat is submerged. The corresponding shear stresses are higher than the critical stress for erosion, thus suggesting possible remobilization of surface sediments.

Moreover, suspended sediment concentrations in the runnel are greater than those associated with the regional tidal flow, and comparable to concentrations during energetic wave conditions. All this evidence indicates that shallow flows in runnels are important morphodynamic agents producing noteworthy geomorphic work.

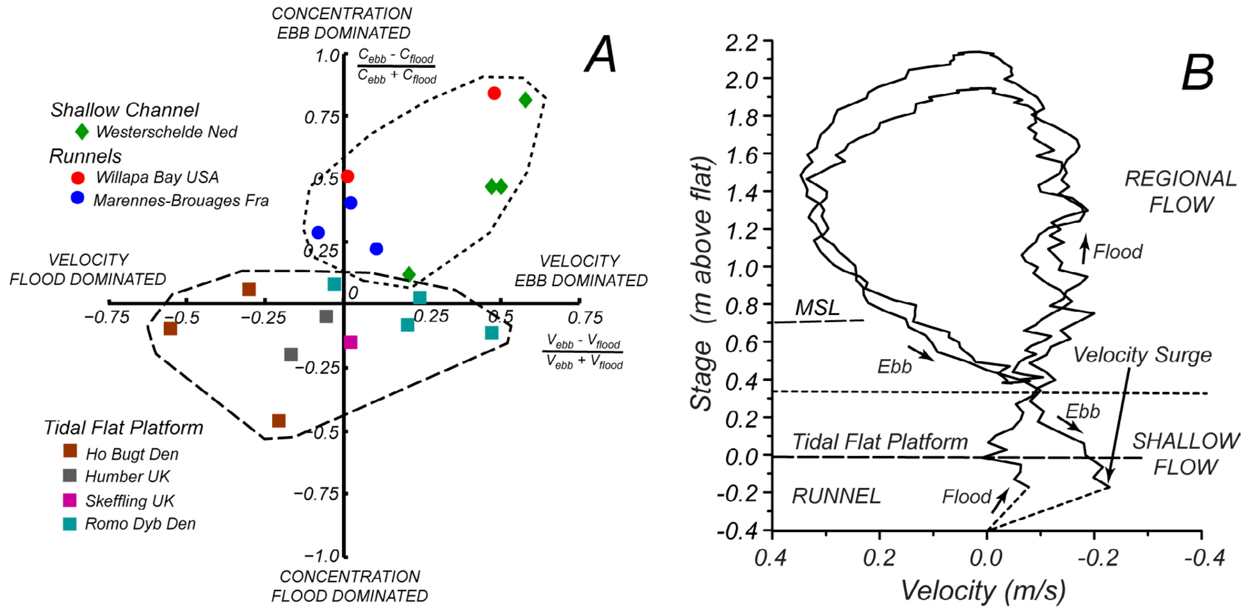

Figure 8. (a) Velocity and sediment concentration asymmetry in shallow mudflat flows. The asymmetry is computed as the normalized difference between the value measured at the lowest water depth during ebb minus the value measured at the lowest water depth during flood. Both values refer to the same wetting and drying cycle and for flows with water depth between 8 and 21.5 cm. (b) Stage-velocity curve in the Willapa Bay runnel for the tide of April 12, 2010. Two flow regimes are evident: the regional tidal flow for water levels above 0.4 m, and a shallow flow, dictated by the wetting and drying of the flat platform, for water levels below 0.4 m. Similarly to salt marshes, the stage-velocity curve for the shallow flow is asymmetric and presents velocity surges (after Fagherazzi and Mariotti 2012).

A MASS-CONSERVATIVE CENTERED FINITE VOLUME MODEL FOR FLUID MUD PROPAGATION OVER VARYING TOPOGRAPHY AND DRY AREAS

We tested the mass-conservative centered finite volume model against both exact solutions and numerical examples. The results show the ability of the model to deal with wetting and drying of both water and fluid mud layers, providing mass-conservative solutions. Moreover, the model solves discontinuities and steep fronts, computing accurate and oscillation-free solutions. In particular, during the propagation of water and mud, low velocities allow the sediment to deposit forming a mud layer, whereas locations with higher velocity trigger sediment entrainment from the mud at the bottom. Results also show that the mud accumulates around obstacles resting with a sloping surface due to plasticity (Bingham fluid). The correct simulation of the propagation of water and mud over complex geometries and the ability of dealing with wetting and drying conditions make this model an ideal tool for the study of water-mud mixtures in mudflats.

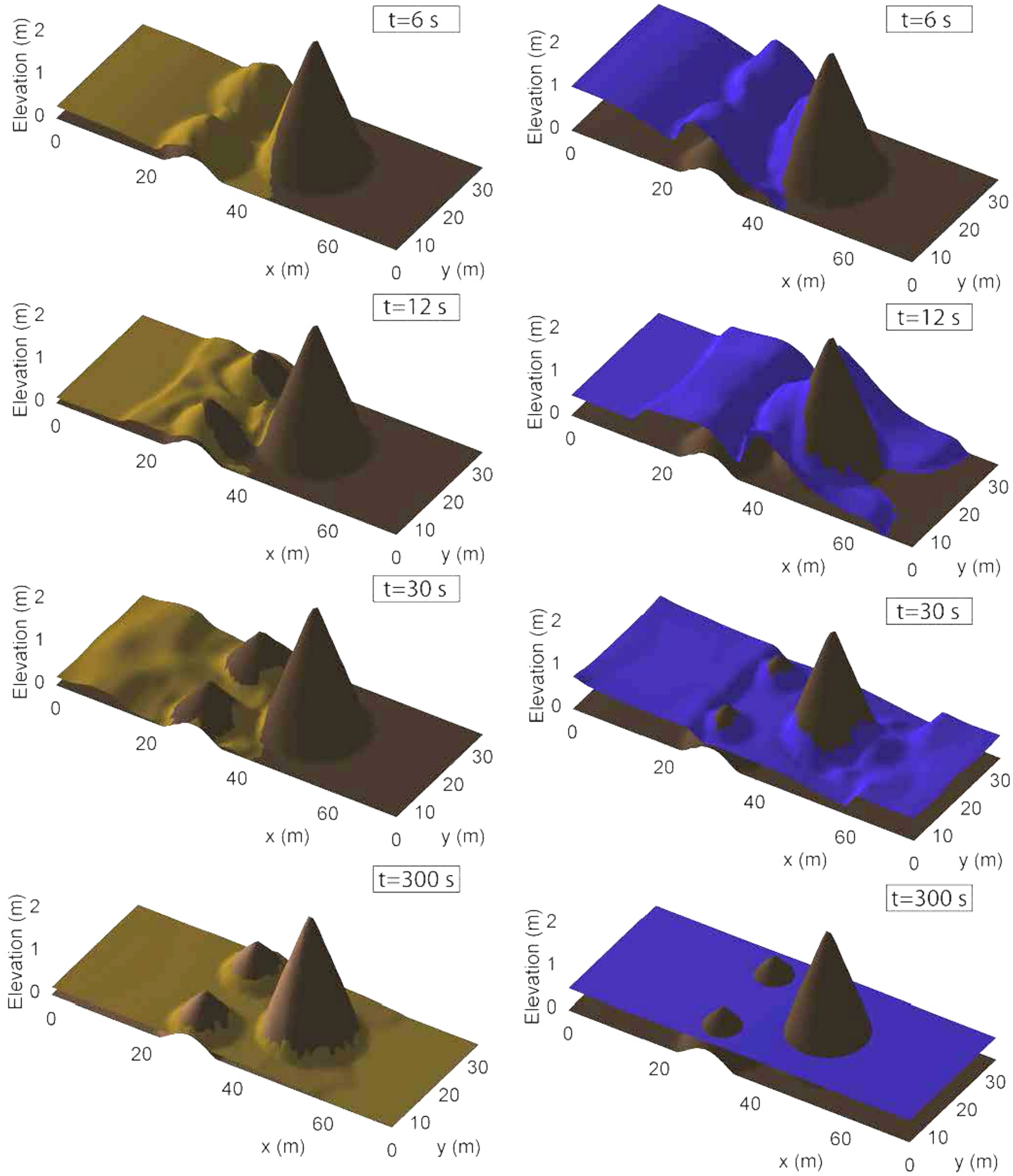

Figure 9. Dam break with a bottom mud layer over a dry bed with three mounds computed using the mass-conservative finite volume model. Results at t = 6, 12, 30 and 300 s for fluid mud surface (left column) and water surface (right column). Bed elevation is also plotted (after Canestrelli et al. 2012).

A DYNAMICAL MODEL FOR THE COUPLED EVOLUTION OF CHANNELS AND TIDAL FLATS

The morphological model shows that, without wind waves, a flat bottom is unstable and the only stable configuration is a channel without tidal flats. For intermediate wave conditions, a non-trivial stable equilibrium arises, characterized by a channel flanked by tidal flats. Intense waves suppress the channelization process, and a flat bed becomes then the only stable equilibrium. Finally, relative sea level rise allows the coexistence of channels and tidal flats, even in absence of waves.

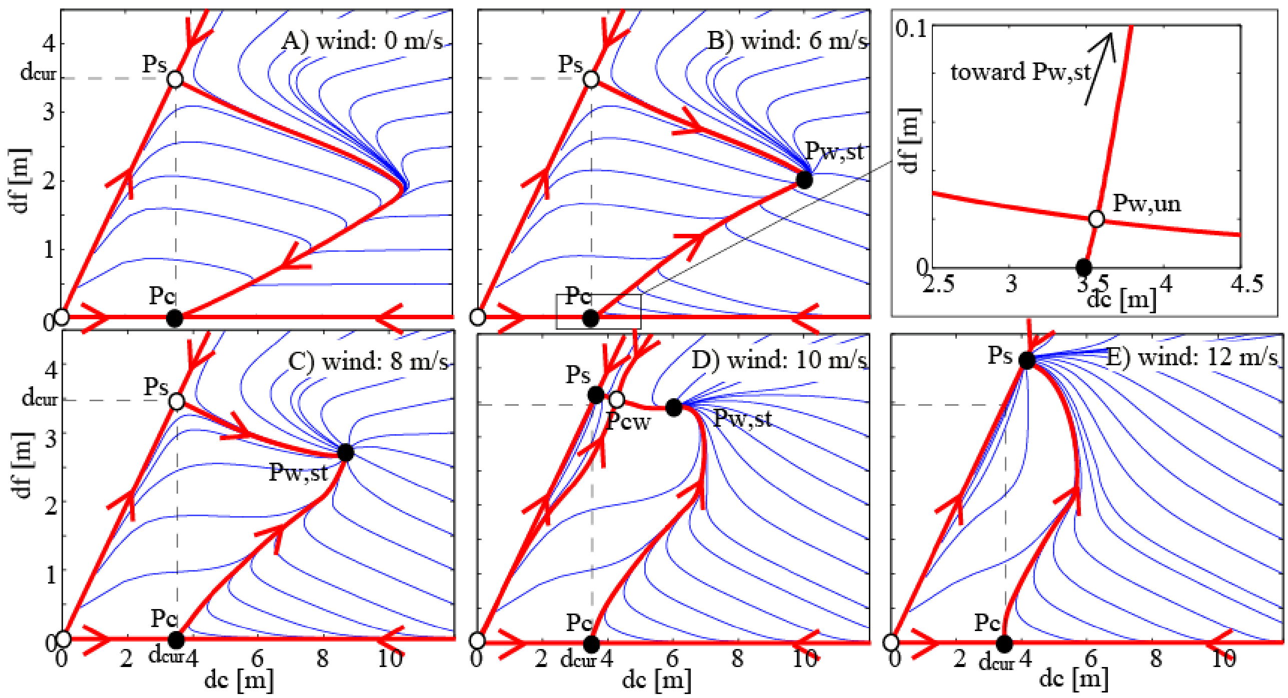

Figure 10. Phase space plot of channel depth (dc) and tidal flat depth (df). Wind speed is varied from 0 to 12 m/s. The major stable (solid dots) and unstable points (empty dots), manifolds (red lines), and some indicative trajectories (blue lines) are reported (after Mariotti and Fagherazzi 2012c).

IMPACT/APPLICATIONS

The collected data will help assessing the navigability and trafficability of mudflats and tidal channels in denied areas. Moreover, the characterization of wave climate along a muddy coast will provide useful information for navigation and landing in very shallow water. Finally, the feedbacks between tides, waves and sediment transport will provide information on the evolution of mudflat environments and their morphological characteristics.

RELATED PROJECTS

The proposed research is designed to synergistically complement the ONR- MURI project "Mechanisms of Fluid Mud Interactions under Waves" and the Willapa Bay "Tidal Flats" ONR-DRI project

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